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Frana, Benjamin Thomas

Annapolis, Maryland. U.S. Naval Postgraduate School

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B. T. FRANA

THE DESIGN OF A LOW-LEVEL TORQUE GENERATING AND INDICATING MECHANISM

by

Benjamin Thomas Frana
Lieutenant Commander, United States Navy

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[redacted]
Chairman

Department of Mechanical Engineering.

Approved:

[redacted]
Academic Dean. acting

PREFACE

Very few instrument components are available that meet the exacting requirements of performance specifications in the field of guidance and control for long range missiles. There is an especial need for the development of a low torque gimbal suspension for gyros and the instruments they actuate. MIT (32).

Under the sponsorship of the Bureau of Ordnance, Dr. E. K. Gatcombe of the U. S. Naval Postgraduate School, Annapolis, Maryland, is engaged in a research project on the utilization of air pressure as a supporting medium for a gyro. Indications are that this method of support will produce torque values of the desired low order. The research project includes the design and construction of a mechanism employing air as a supporting medium.

It is a well known fact that the torque required to put a rotor in motion, that is, the breakaway torque, is much greater than the torque required to keep the rotor in motion due to the necessity of overcoming static friction. The Bureau of Ordnance is particularly concerned about the high breakaway torques in present methods of gyro supports and the erratic outputs caused by these high breakaway torques.

The proposed gyro unit, which will utilize air pressure as a supporting medium, will have a solid metal rotor equivalent in weight to typical gyro. Some means must be available to impart a measurable torque to the gyro rotor for producing breakaway from the stationary position.

<u>This thesis is the design of a low-level torque generating and indicating mechanism</u>. The order of magnitude of the torque expected to be encountered in the proposed gyro unit is from 1 to 100 dynecentimeters and the mechanism is to be designed to cover that range.

The design of this low-level torque generating and indicating mechanism was undertaken by the writer during January - April 1949 at the U. S. Naval Postgraduate School, Annapolis, Maryland. The final design was completed during the first part of April. At the time of this writing (April 1949) the mechanism is being manufactured in the machine shop of the Postgraduate School.

The author wishes to express his appreciation to Dr. E.K. Gatcombe for entrusting him with the fulfillment of this part of his research project and for his guidance and assistance in the design of the mechanical parts of the mechanism. Likewise he wishes to express his appreciation to Professor C. B. Oler of the Department of Electrical Engineering for his suggestions in the design of the electrical parts of the mechanism.

The author is further indebted to a number of people for their helpful criticisms. Several members of the staff commented on the various proposed methods for generating and measuring torque. The criticisms of the sundry officials of the Bureau of Standards were especially useful. The practical suggestions of the machinists of the P. G. School machine shop were invaluable.

The Librarian of the U. S. Postgraduate School and his staff were extremely efficient in locating or procuring desired references. Lastly, the author wishes to express his appreciation to the staffs of the libraries at the U. S. Naval Experiment Station and the U. S. Naval Academy.

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TABLE OF SYMBOLS AND ABBREVIATIONS

A - Area of a condenser plate.

C - Capacitance.

C_e - Edge effect capacitance.

C_n - Normal capacitance.

C_p - Total capacitance for a parallel plate condenser.

D - Diameter of condenser plate.

E - Potential difference on the individual condensers of series-connected condensers.

f - Force.

K - Dielectric constant.

L - Length.

σ - Charge per unit area.

Q - Charge.

s - Separation between condenser plates.

t - Thickness of condenser plate.

T - Torque.

uuf - Micromicrofarads.

V - Line voltage and potential difference of a single condenser in volts.

V_s - Potential difference in statvolts.

x - t divided by s.

z - $f(x) = (1 + x) \ln (1 + x) - x \ln x$.

CHAPTER I

INTRODUCTION

1. Desirable Characteristics of the Proposed Mechanism.

It is desirable that the mechanism for indicating and generating low-level breakaway torques be as simple as possible to construct and operate, and yet rugged. The gyro unit will have to operate at some angle between the horizontal and the vertical so that the mechanism must likewise function at any angle. It should be capable of producing accurate results and these results should be reproducable within experimental error under identical conditions.

It must be capable of producing and indicating torque of the order of magnitude of one or more dyne-centimeters. In this respect a milligram weight at one centimeter distance from a fulcrum produces roughly one dyne-centimeter of torque.

The mechanism should be frictionless, if possible. If that is not possible, it should not produce an uncertainity (or unknown) torque. A mechanism with a known breakaway torque might be acceptable provided that this known breakaway torque is less than the smallest quantity of expected measurement, namely, one dyne-centimeter of torque.

The mechanism should not introduce any vibration into the gyro unit since vibration would impair the stability of that unit. The use of air as a supporting medium may introduce critical conditions under some circumstances which are susceptible to vibration. Any mechanism with tendency to cause unbalance is unacceptable because unbalance would result in vibration and malfunctioning of the gyro unit.

One degree of rotation of the gyro shaft from the stationary position will be considered sufficient motion for producing breakaway. Any proposed mechanism should, if possible, incorporate means for indicating the instant breakaway occurs.

2. Methods Investigated.

The use of alternating current equipment such as an induction motor, a selsyn, or a transformer would provide a frictionless means of obtaining torque. Measured values of the voltage and current required could be interperted as torque. However, the use of alternating current would increase the possibility of vibration of the gyro unit.

The objection to the use of alternating current would be overcome by the use of a direct current electrical instrument, such as the common voltmeter of the D'Arsonval type. This type is based on the principle of a coil turning in a magnetic field. The torque is practically proportional to the voltage. The instrument could be converted to torque generating and indicating use by coupling in some manner the shaft of the moving coil of the voltmeter to the shaft of the gyro rotor. The difference between the readings of the coupled voltmeter and another voltmeter in the line would be an indication of the torque required by the gyro unit. Another method of using the voltmeter would be to replace the spiral springs by electrical lead-in pigtails and couple the moving coil to the gyro shaft. However, in each case, uncertainity would exist about the breakaway torque of the jewel bearings of the voltmeter. Dawes (11). Rhodes (39).

Direct current motors would provide an indication of torque by their current demand. But the breakaway torque of either a D.C. motor coupled to the gyro rotor shaft or a D.C. motor built directly on the rotor shaft with its commutator brushes bearing against the shaft would be uncertain and in any case would exceed the expected breakaway torque of the gyro unit. The same conditions would hold in a D.C. motor which would receive armature current by flexible electrical pigtails. Roberts (40).

A D.C. selsyn receiver unit consists essentially of a stationary delta winding surrounding a permanent magnet rotor. The permanent magnet rotor could be mounted on the gyro rotor shaft and the weight of the permanent magnet rotor included as part of the gyro rotor. Such a system would be a frictionless way of producing torque. The torque would be proportional to the current and voltage required. However calculations showed that this system would not be sufficiently sensitive to produce low-level values of torque. This objection holds for all types of moving-magnet rotor instruments. Faus (13). Jewell (25). Johnson (26). Manildi (30). Mendelsohn (33). Sias (44).

Torque can be measured by a torsion wire. Some method must be provided for generating the torque. Measurement would have to be made of the torque of the generating mechanism and then of the combined torque of the mechanism and the gyro unit. The difference in torque between the two measured quantities would be the torque of the gyro unit. A highly intricate system is required for aligning the wire. The wire is susceptible to mechanical hysteresis. In addition an error torque would arise from the uncertainty in calculating torque in connecting the ends of the wire. MIT (32). Strong (48).

Another method investigated was that of producing torque by heating one end of a rod attached at its longitudinal midpoint to the gyro rotor shaft. To obtain the torque the rod is placed in a horizontal position and heat is applied to one end of the rod. The temperature gradient in the rod causes greater expansion of the heated end than the other end. This results in the center of gravity of the heated end moving away from the longitudinal midpoint more than the center of gravity of the other end moves away from the longitudinal midpoint and an unbalance is caused. This unbalance produces a breakaway torque. By considering the theories of heat conduction, radiation, and convection it was calculated that a half inch diameter and four inch long iron rod in a horizontal position would produce 68.6 dyne-centimeters of torque after one of its ends has been heated at a temperature of 270 degrees

Farenheit for five minutes. The initial temperature was 70 degrees Farenheit. Boelter (5). Carslaw (9). Fourier (14). Jakob (22). Ingersoll (23). The amount of torque available could be determined from the current and voltage needed by the electric light used for heating the end of the rod as well as the measurement of the expansion of the rod. Because of the uncertainity of heat convection affecting the rod and the difficulty in concentrating the heat of an electric light on one end of the rod, it was decided not to use this method. Furthermore, the unbalance weight involved would vary as the sine of the angle measured from the horizontal so that when the gyro rotor shaft was in a vertical position, no torque would be obtained.

The Rayleigh Disk principle is that an ellipsoid of revolution experiences a torsional moment when emersed in a moving fluid. For a disc of radius a, thickness c, velocity of fluid W_o, angle with direction of fluid flow θ, and density of fluid w, the torsional moment is

$$\frac{2}{3} w a^2 \left(1 - 0.2977 \frac{c}{a}\right) W_o^2 \sin 2\theta$$

A disk two inches in diameter and one-sixteenth inch thick in an air stream flowing at a velocity of one to two feet per second would provide the required torque. The exact measurement of the air velocity would be difficult since present day pitot tubes are not very sensitive at low velocities of air flow. Strong (48).

Torsion springs are used as hairsprings in watches and are also used in some electrical instruments. At first glance they appear attractive for low-level torque generation. Upon study of their principle of operation they are eliminated as a possibility for such utility. Their most effective use is in positions where a very large angle of torsion is available between two connections. For measuring breakaway torque a large angle of torsion is unnecessary. Only approximate formulas are in use for torsion springs and these might be considerably in error under certain circumstances. In the derivation of these formulas the assumption is made that the coils behave as if they were equivalent to a straight beam equal in length to the wire in the spring. This assumption is not entirely valid so that computed values must be checked by actual tests. Furthermore, inaccuracy of computations arises from uncertainity as to the exact way in which the ends are held and the torque applied as well as from uncertainity as to how perfectly the coils remain apart during twist. Spiral springs such as used as mainsprings in watches are so flexible that when loaded some leaves deform and come in contact so that the loading condition stipulated at the start of an analysis is violated and any assumption that the spring is in the shape of a spiral does not hold. Van Den Broek (51). The order of these uncertainties is greater than the desired order of measurement. Ault (2). Barr (3). Timoshenko (49). Wahl (52).

It would be possible to obtain the desired low-level torque generation by use of minute highly-stabilized permanent magnets. Such a device would consist of a bar magnet attached to the shaft of the gyro rotor and attracted by two bar magnets located near the ends of the bar magnet attached to the shaft. These two bar magnets would be mounted in a movable cradle which could be accurately positioned by a micrometer screw. Investigation showed that the effect of the earth's magnetism on the small permanent magnets would be of sufficient degree to cause intolerable inaccuracies. In addition precautions would have to be taken against vibration, impact, and stray magnetic fields. Attwood (1). General Electric (16). Gray (19).

Torque can be produced by the application of a force on a lever arm at a distance from a fulcrum. Provided that the force and distance are accurately known this method produces a high degree of accuracy. Such a device would consist of an arm attached to the rotor shaft on which known weights could be placed at various distances from the fulcrum. The torque at any angle of inclination from the horizontal of the gyro rotor shaft will vary as the sine of that angle.

For a difference of potential between the plates of a parallel plate condenser, a force exists which tends to draw the two plates together. This force in dynes for a parallel plate condenser in air may be expressed by

$$f = \frac{V_s^2 A}{8 \pi s^2}$$ Brooks (7).

where V_s is the potential difference in statvolts,
A is the area of the plate in square centimeters,
s is the separation of the plates in centimeters.

or by the equivalent formula

$$f = \frac{1}{2} \frac{C V^2}{s} \times 10^{-5}$$

where C is the capacitance between the plates in micromicrofarads,
V is in volts.

Torque is equal to force time length. By mounting one of the condenser plates on a stationary support and the other condenser plate on an arm attached to the rotor shaft it is possible to construct a torque generating mechanism. The amount of voltage impressed would be an indication of the torque generated for a given plate size and spacing between plates. Dawes (11). Starling (47).

3. Method Selected.

The utilization of the property of capacitance as produced by the application of a potential difference between the plates of a condenser was selected for the design of the torque generating and indicating mechanism since it possesses many desirable characteristics which can be used to advantage in the mechanism. In general terms the actuating force for the mechanism will be produced by the capacitance effect between two parallel plates--one of the plates to be stationary and the other to be attached to an arm extending from the rotor shaft. For various definite spacings the voltage required would be a direct indication of the torque generated. By using a low value of voltage, a low order of magnitude of torque could be obtained. This mechanism would provide a frictionless way of producing torque--the weight of the gyro rotor could be reduced to compensate for the weight of the movable plate and its arm. The mechanism can be made of as rugged construction as desirable and it can be operated in any position. It can be remotely operated. The utilization of the capacitance method will give a quick positive indication of breakaway torque without any detecting equipment because as soon as the voltage is sufficient to move the plate attached to the arm, the plate will move until it strikes the other plate. As shown by the basic parallel plate condenser formula, the force increases as the space between plates decreases.

As a testing procedure selection was made of the fundamental method of producing a torque by using known weights on a lever arm at a definite distance from a fulcrum. With a definite spacing between condenser plates, a certain voltage will be required to produce breakaway torque under particular conditions of shaft loading. If these conditions of shaft loading are held constant and a known weight is added to the condenser plate arm at a fixed distance from the center of rotation than an increased voltage will be necessary. This actual increased voltage should check with the value of increased voltage as determined by computation.

CHAPTER II

METHOD OF UTILIZING THE CAPACITANCE PRINCIPLE

1. Theory of Parallel Plate Condensers.

When a potential difference is applied between the plates (only two plate condensers will be considered) of a parallel plate condenser, electricity is stored in the condenser with positive charges existing on one plate and negative charges existing on the other plate. This property of a condenser--the ability to store electricity--is called capacitance. A condition of stress exists in the medium in the neighborhood of an electric charge, and force acts on a positive or negative charge placed in the medium. The region in which the condition of stress exists is called the dielectric or electrostatic field and this condition of stress may be represented by lines known as dielectric lines.

The capacitance in electrostatic units of a parallel plate condenser is

$$C = \frac{1}{4} \frac{K A}{\pi s} \qquad \text{Dawes (11).}$$

where C is in statfarads,

A is the area of the plate in square centimeters,

K is the dielectric constant.

Air will be used as the dielectric. The dielectric constant of air has been determined as 1.0006 by the National

S = thickness of dielectric "

Bureau of Standards. Brooks (7) . Unity will be used as the dielectric constant for air.

Converting the above formula to practical units, the formula becomes

1 STATOHM = 9×10^{11} OH

1 FARAD = 10^{6} MICR

$$C = \frac{A}{4\pi s \times 9 \times 10^{5}} \text{ microfarads}$$

or

$$C = \frac{A}{4\pi s \times .9} \text{ micromicrofarads.}$$

Since better distribution of dielectric lines is obtained with circular plates, the area for a circle ($A = .25\, D^2 \pi$) will be substituted in the formula and it now becomes

$$C = \frac{.25\, D^2 \pi}{4\pi s \times .9} \text{ micromicrofarads}$$

$$= .0696 \frac{D^2}{s} \text{ uuf}$$ (uuf is the symbol for micromicrofarads).

4

Later in the text this C will be considered as C_n. So that $C_n = C = .0696 \frac{D^2}{s}$ uuf.

4

However, the total capacitance of a simple plate condenser is not accurately given by this formula since all the dielectric lines do not lie in the region between the plates but some of the lines pass from the back of the positive plate to the back of the negative plate. These lines that pass between the backs of the plates exert a "fringing" or "edge" effect which increases the capacitance of the condenser.

Lord Kelvin in about the year 1870 compensated for the edge effect by surrounding one of the plates with a "guard ring" and electrically connecting it to that plate. The other plate was increased to the outer diameter of the guard ring. Kelvin (27).

Kirchoff in his work "On the Theory of Condensers" in 1878 set forth formulas for edge effect capacitances. These formulas have been checked experimentally by Mr. Hoch of the Bell Laboratories (21) and Messers Scott and Curtis (43) of the National Bureau of Standards and found to be within experimental error. A "guard ring" condenser was used as the standard. The mechanism will be simpler to construct and will be smaller in size without a guard ring.

Kirchoff's formula for the edge effect capacitance is: Hoch (21).

$$C_e = \frac{D}{25.1}\left[\ln\left(\frac{25.1\ (s+t)D}{s^2}\right) + \frac{t}{s}\ \ln\left(\frac{s+t}{t}\right) - 3\right] \text{uuf}$$

where t is the thickness of plate in centimeters.

This formula may be more conveniently expressed in an equivalent form as follows: Scott (43).

$$C_e = .0442D\left[\ln\left(\frac{25.1\ D}{s}\right) - 3 + z\right] \text{uuf}$$

where $z = f(x) = (1 + x) \ln (1+x) - x \ln x$,

and $x = \frac{t}{s}$.

Values of z for certain values of x can be obtained from Scott (43).

The second formula will be used for the values of x given on page 751 in Reference 43. The first formula will be used otherwise.

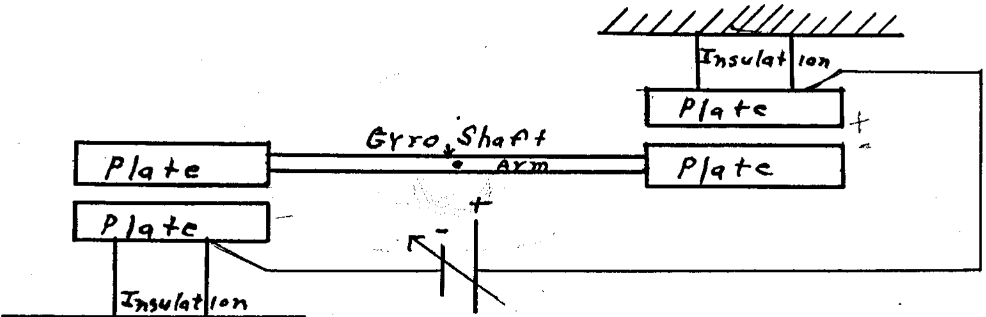
The total capacitance for a parallel plate condenser is the direct (or normal) capacitance plus the edge effect capacitance. Stated in formula it is

$$C_p = C_n + C_e .$$

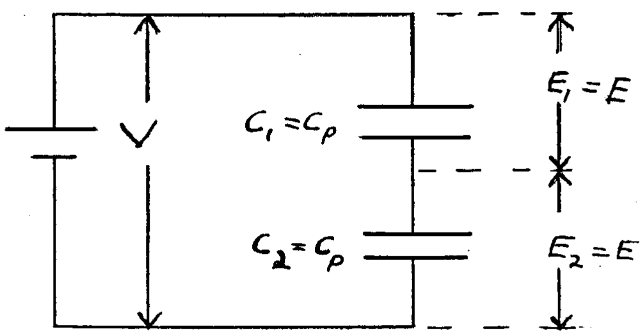
2. Arrangement of Parallel Plate Condensers.

It had been previously proposed to provide a stationary support for one of the plates and to attach the other plate to an arm leading from the rotor shaft. The electrical connection to the stationary plate consists of merely soldering an electrical pigtail to it. However the soldering of a pigtail to the plate on the arm will introduce an uncertain torque in excess of one dyne-centimeter into the mechanism. An electrical connection to the gyro housing would not be satisfactory because when the gyro is supported by air pressure there will be no electrical contact between the housing and the gyro shaft.

To eliminate the need for an electrical connection to the plate on the arm, use is made of two condensers in series. A double arm in the form of a lever pivoted at its longitudinal center is used with each end of the arm carrying a condenser plate. A stationary plate is located opposite each condenser arm plate as shown



The system is equivalent to two identical condensers in series as shown in this schematic diagram



where V is the line voltage in volts, E is the voltage across each condenser in volts and C_p is the charge across each condenser in farads.

Now $V = E_1 + E_2 = 2E$

and $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} = \frac{1}{C_p} + \frac{1}{C_p}$

then $\frac{1}{C} = \frac{2}{C_p}$

11/3/2 or $C = \frac{C_p}{2}$

where C is the total charge of the two series connected condensers in farads. Dawes (11).

3. Derivation of the Formula for Torque.

The force in dynes on a plate of a parallel plate condenser is

$$f = 2\pi\sigma^{-2} A \text{ dynes}$$

where as before, A is the area of the plate in square centimeters,

and σ is the charge per unit area in electrostatic units per square centimeter and is equal to

$$\frac{Q \text{ (statcoulombs)}}{A \text{ (square centimeters)}}$$

Now $Q \text{ (coulombs)} = C \text{ (farads)} \times V \text{ (volts)}$,

or $$\frac{Q \text{ (statcoulombs)}}{3 \times 10^{9}} = \frac{C \text{ (statfarads)}}{9 \times 10^{11}} \times V \text{ (volts)},$$

and $$Q \text{ (statcoulombs)} = \frac{C \text{ (statfarads)}}{300} \times V \text{ (volts)},$$

by substitution

$$f = \frac{2\pi C^{2}\text{(statfarads) } V^{2}\text{(volts)}}{A} \times \frac{1}{(300)^{2}} \text{ dynes}$$

and $$C \text{ (statfarads)} = \frac{A \text{ (square centimeters)}}{4\pi s \text{ (centimeters)}},$$

so $$f = \frac{6 \text{ (statfarads) } V^{2} \text{ (volts)}}{2 s \text{ (centimeters) } 90{,}000} \text{ dynes;}$$

since $C\ (uf) = C\ (statfarads) \times 9 \times 10^5$,

and $C\ (uuf) = \dfrac{C\ (statfarads) \times 9}{10}$

so $f = \dfrac{V^2\ (volts)\ C\ (uuf)}{2\ s\ (centimeters)} \times 10^{-5}$ dynes.

Substituting $C = \dfrac{C_p}{2}$ in the formula

$$f = \frac{1}{4} \frac{C\ (uuf)\ V^2\ (volts)}{s\ (centimeters)} \times 10^{-5} \text{ dynes.}$$

Now $T = f \times L$

where T is torque in dyne-centimeters,

L is length in centimeters.

so $T = \frac{1}{4} \dfrac{L\ C\ V^2}{s} \times 10^{-5}$ dyne-centimeters.

4. Choice of Maximum Voltage.

A wide range of torque values will be obtained by using voltages between 0 and 600 volts. The maximum value of 600 volts is considered safe for laboratory use. It is readily obtained by using two 300 volt commercial dry cell batteries in series.

The use of a 50,000 ohm gang potentiometer (double coil) puts a 100,000 ohm resistance between the battery terminals. When the circuit is energized, such a resistance with an impressed potential of 600 volts causes 6 milliamperes to flow. A current of such magnitude is not dangerous to personnel.

The current caused by the discharge of a condenser of less than 100 micromicrofarads in size is not dangerous to personnel. The size of the condensers to be used will be about 5 micromicrofarads.

5. Determination of Length of Arm and Size of Plates.

To preclude any possibility of longitudinal unbalance of the gyro unit it was considered necessary to mount a condenser arm (carrying two plates) at end of the gyro shaft. By several trial calculations it was determined that a condenser plate of one inch in diameter and a lever arm of one and one half inches in length would furnish the desired torque provided that the voltage could be varied from 0 to 600 volts and the separation of the plates from 0.5 centimeters (0.1968 inches) to 0.1587 centimeters (0.0625 inches).

In order to obtain a low value of edge effect and yet a rigid condenser plate, the thickness of the condenser plate was chosen as 0.5 centimeters. The smallest separation--0.1587 centimeters--allows for a gyro shaft rotation of one degree and forty-eight minutes before the plates touch. Specially, with the largest separation and a voltage of 100 volts a torque of 0.484 dyne-centimeters is obtained. With the smallest separation and a voltage of 600 volts a torque of 162.5 dyne-centimeters is obtained. these values cover the range of expected operation. The calculation of these values is given in Appendix I.

CHAPTER III

DESIGN OF THE COMPONENT MECHANICAL PARTS

1. Condenser Disc Arm and Attachments.

For the sake of clarity the arm carrying the condenser plates will be labelled as the condenser disc arm and the condenser plates on it as condenser discs. To facilitate machining and obtaining of exact symetry it was decided to make the discs and the arm leading to the discs of the same dimension in thickness except that the tolerances on the disc must be held to 0.0001 inches by grinding and the faces of the discs must be absolutely parallel. The condenser disc arm is shown in detail as Piece No. 1 of Illustration 1.

The material chosen for the condenser disc arm is Ry-Alloy Tool Steel. Ryerson (41). It is a manganese molybdenum high carbon, oil hardening, non shrinking steel. It is made under exacting control in both melting and finishing operations to secure the maximum possible uniformity of hardening and shrinkage properties. It will provide an extremely hard surface with minimum change of shape and yet retain a high degree of toughness.

The projection of the condenser disc arm from the center of the gyro shaft is equivalent to a cantilever beam. The maximum force expected at the center of each condenser disc is 25 dynes. With this force a deflection of 0.128×10^{-8} inches will be produced at the center of a condenser disc on the condenser disc arm. Eshbach (12).

This deflection indicates that the condenser disc arm is of such dimension as to be sufficiently stiff.

The condenser disc arm has a centrally located hole for press fitting on the gyro shaft whose diameter is 0.2001 + .0004 or -.0000 inches. The hole diameter is 0.2000 + .0004 or -.0000 inches. These tolerances are for a medium force fit. Gatcombe (15).

During the layout of the condenser disc arm a vertical mark should be scribed at its longitudinal center. After machining the balance of the arm should be checked on a sharp knife edge and the arm either placed in balance by further machining within specified tolerances or the arm discarded.

The arm is tapped in its horizontal centerline for No. 3 screws. Pegs are made from No. 3 screws in accordance with the dimensions of Piece No. 2 of Illustration 1. The pegs are drilled with a No. 80 drill. When the pegs are mounted, a wire will be threaded through them and secured tautly by upsetting. It will provide a securing position for weights which is practically on the horizontal centerline of the condenser disc arm. The wire is Piece No. 3 of Illustration 1.

To provide for a fine degree of balance the condenser disc is tapped for a one-sixteenth inch screw and balancing screws (Piece No. 36) and balancing nuts (Piece No. 37) installed as shown on Illustration 7.

The weight of the condenser disc arm and attachments is 50.8 grams for one unit or 0.224 pounds for the two units required. This weight may be considered as part of the gyro rotor unit.

2. Condenser Plate and Supporting Attachments.

The condenser plate (Piece No. 4 of Illustration 1) is to be of the same material as the condenser disc and as carefully machined. This plate must be electrically insulated from the housing of the gyro unit. This is accomplished by the use of a seasoned maple pedestal shown as Piece No. 6 of Illustration 1. Wood is a good insulator for direct current and the chosen length of wood is sufficient insulation to make negligible any capacitance effect between the condenser plate and the metal supporting structure. Piece No. 5 of Illustration 1 is a screw which secures the plate to the pedestal.

The pedestal has a running fit in the guide (Piece No. 7 of Illustration 2). The pedestal is held snugly in position by a spring which is shown as Piece No. 9 of Illustration 2.

Between the largest separation of 0.1968 inches and the smallest separation of 0.0625 inches a distance of 0.1343 inches is available for a spring. Another 0.1 inch is allowed for putting the spring under load. Then by consulting Reference 39 it was found that a No. 12 Gage Music wire gives a deflection of 0.365 inches per coil. It was decided to use one turn of this gage wire as a spring for Piece No. 9 since it would amply support the load. Its free length was calculated as 0.393 inches and its compressed length as 0.028 inches.

For raising and lowering the pedestal and condenser plate Piece No. 10 of Illustration 2 is threaded through the guide and into the pedestal. It is actuated by the thumb screw (Piece No. 11 of Illustration 2). The guide is supported on bushings (Piece No. 13 of Illustration 2) accurately dimensioned in length to provide level condenser plates. The bushings encase bolts (Piece No. 12 Illustration 2) which screw into the bedplate. This bedplate (Piece No. 33 of Illustration 6) provides the base for the condenser plate supports and will serve as a base for the gyro rotor casing. The centerlines for the bolts must be spaced on the bedplate within 0.0001 inches to give the proper co-axialism between each supported condenser plate and its corresponding disc on the condenser disc arm.

The bushing length for the lower support is chosen as two inches in order to provide access for manipulating the thumb screw ih lowering and raising the condenser plate. By totaling the vertical dimensions on all parts between the bedplate and the centerline of the condenser disc arm including 0.100 inches for the spring and 0.1968 inches (0.5 centimeters) for the separation between plates a distance of 4.840 inches is obtained. Similar separation and spacing allowance are used on the upper condenser plate and a length of bushing of 7.430 inches is obtained.

(Piece No. 15 of Illustration 3). The bolt used with the bushing is Piece No. 14 of the same illustration.

The machining of the guide, bushing, bolts, and bed plate is not required to be as exact as that of the condenser disc arms and the condenser plates. A SAE 1030 steel is used for these parts.

3. Arresting Post.

The striking of the condenser plates on the arm against the supported condenser plate when a potential difference is applied to them is liable to cause misalignment of the plates and resulting inaccuracies. To preclude this possibility, an arresting attachment is located on each lower support guide consisting of an arresting post, an arresting post guide, a spring, and a screw for adjusting the guide. These are shown as Pieces Nos. 16, 17, 18, and 19 of Illustration 3. The spring (Piece No. 18) must be of such construction that it will stop the motion of the condenser disc arm within one-sixteenth inch of travel at the outer edge of the disc arm--this being the smallest designed separation. It is feasible to locate the arresting post at three-quarters of an inch from the vertical centerline of the condenser disc arm. The amount of travel by the condenser arm permissible at that point is calculated to be 0.023 inches. A spring of Music wire, Gage No. 22, with an outside diameter of one-fourth inch was chosen. Oberg (39). The deflection per turn of such a spring is 0.0127 inches. The use of one turn allows a clearance of 0.01

inches between the condenser disc arm and the arresting post for the smallest designed separation. Instead of a wire spring a better choice for this spot would be a spring washer. A search is being made for a suitable spring washer.

4. Support Post.

A support post and guide prevent the rotation of the condenser disc arm and hold it in a horizontal position when weights are placed on the weight wire. (Pieces No. 20 and 21 of Illustration 3). The support post is located only on the same side of the shaft as the upper condenser plate.

5. Leveling Attachment.

The condenser disc arm is maintained in a level position by two screws on a leveling post. The leveling post rides an eccentric. Just prior to application of voltage the leveling post is allowed to drop in its guide by manual turning of the eccentric. For ease of manipulation a knurled knob and a small shaft are connedted to the eccentric. These component parts are Pieces Nos. 22, 23, 24, 25, 26, 27, and 28 in Illustration 4.

6. Test Block Equipment.

Equipment was selected and designed for blocktesting the torque mechanism prior to installation on the gyro rotor unit framework. Pressurized fluid spherical bearings have been developed by the Barden Bearing Company. MIT (32). Test results show that these bearings have very low breakaway torque. Use is made of two of these bearings. The bearings (Piece No. 35 of Illustration 8) are placed in housings (Piece No. 29 of Illustration 5) which are bolted to the bedplate. The bolt holes in the housings are drilled oversize to permit accurate alignment of the bearings. Piece No. 32 of Illustration 6 is a bearing plate which holds the bearing in its housing.

The gyro rotor is represented by the shaft passing through the bearings. As previously stated, the condenser disc arms will be press fitted on the ends of the shaft. The length of the shaft, as shown in Illustration 5 as Piece No. 30, is 9.300 inches long. It is shouldered to permit accurate location against the shoulders of the spherical balls of the fluid bearings.

7. Manufacture and Assembly.

For convenience of use during manufacture of the mechanism, Illustrations 1-6 were made into one blueprint. Another blueprint was made of the assembly drawing in left side elevation of Illustration 7, the assembly drawing in front elevation of Illustration 8, and Illustrations 9, 10, and 11. These last three illustrations consist of the Bill of Materials and Manufacturing Notes.

During assembly the condenser discs must be placed concentrical with their associated condenser plates. This condition will be fulfilled when the inner edge of the condenser disc arm is 1.5626 +.0001 or -.0001 inches from the outer face of the adjacent bearing housing.

Detail Drawing of Pieces No. 1-6

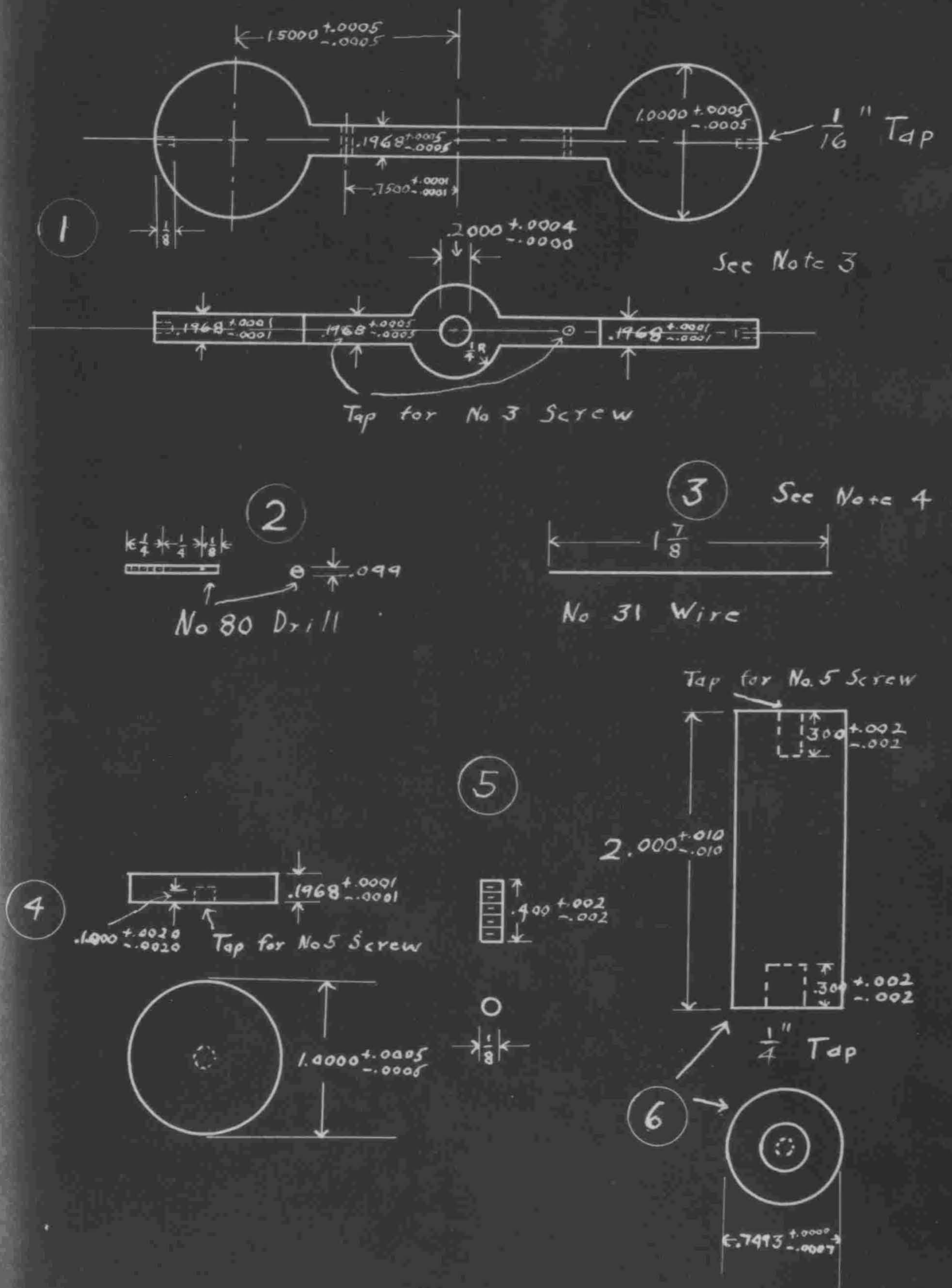


Illustration 1

Detail Drawing of Pieces No. 7-13

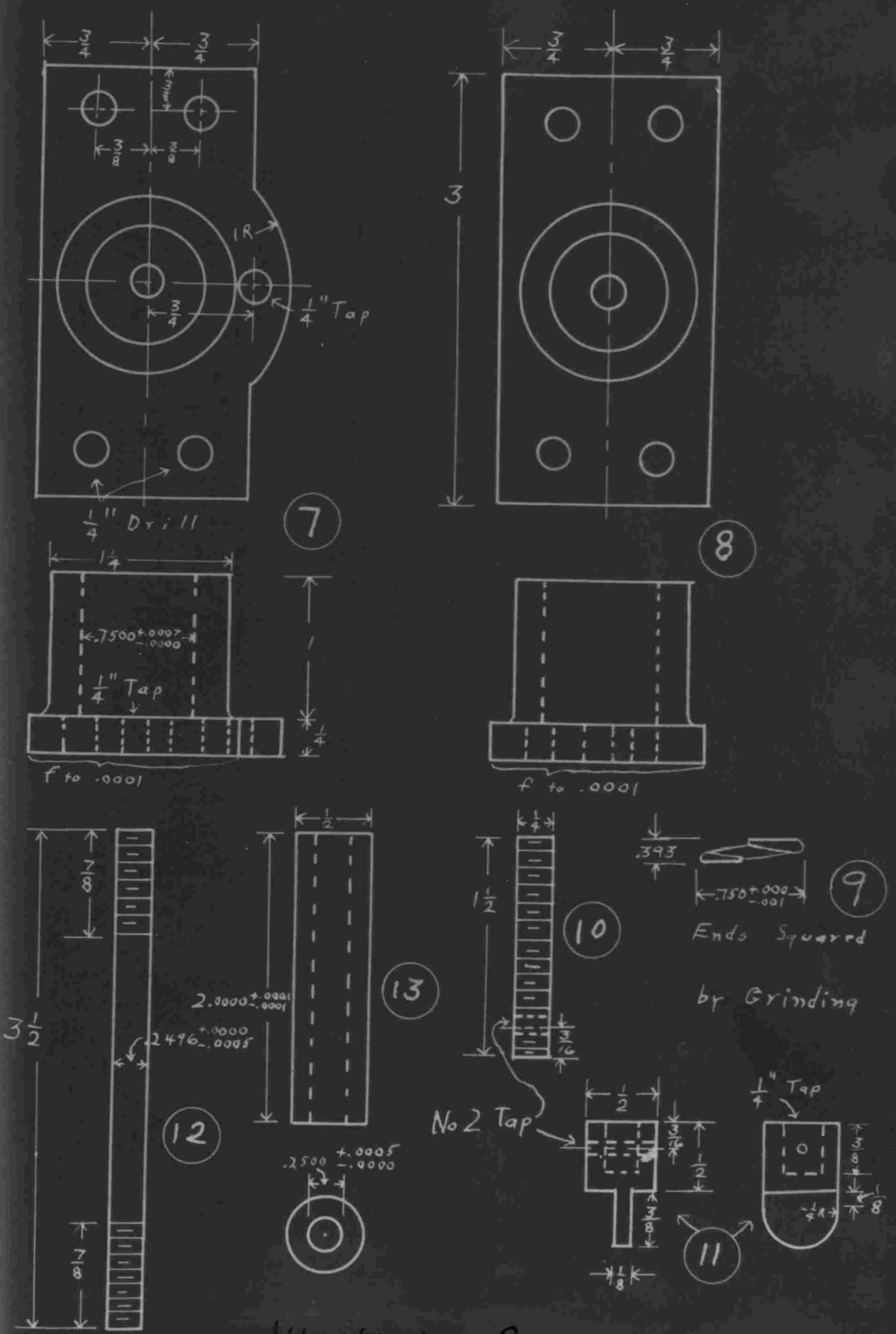


Illustration 2

Detail Drawing of Pieces No. 14-21

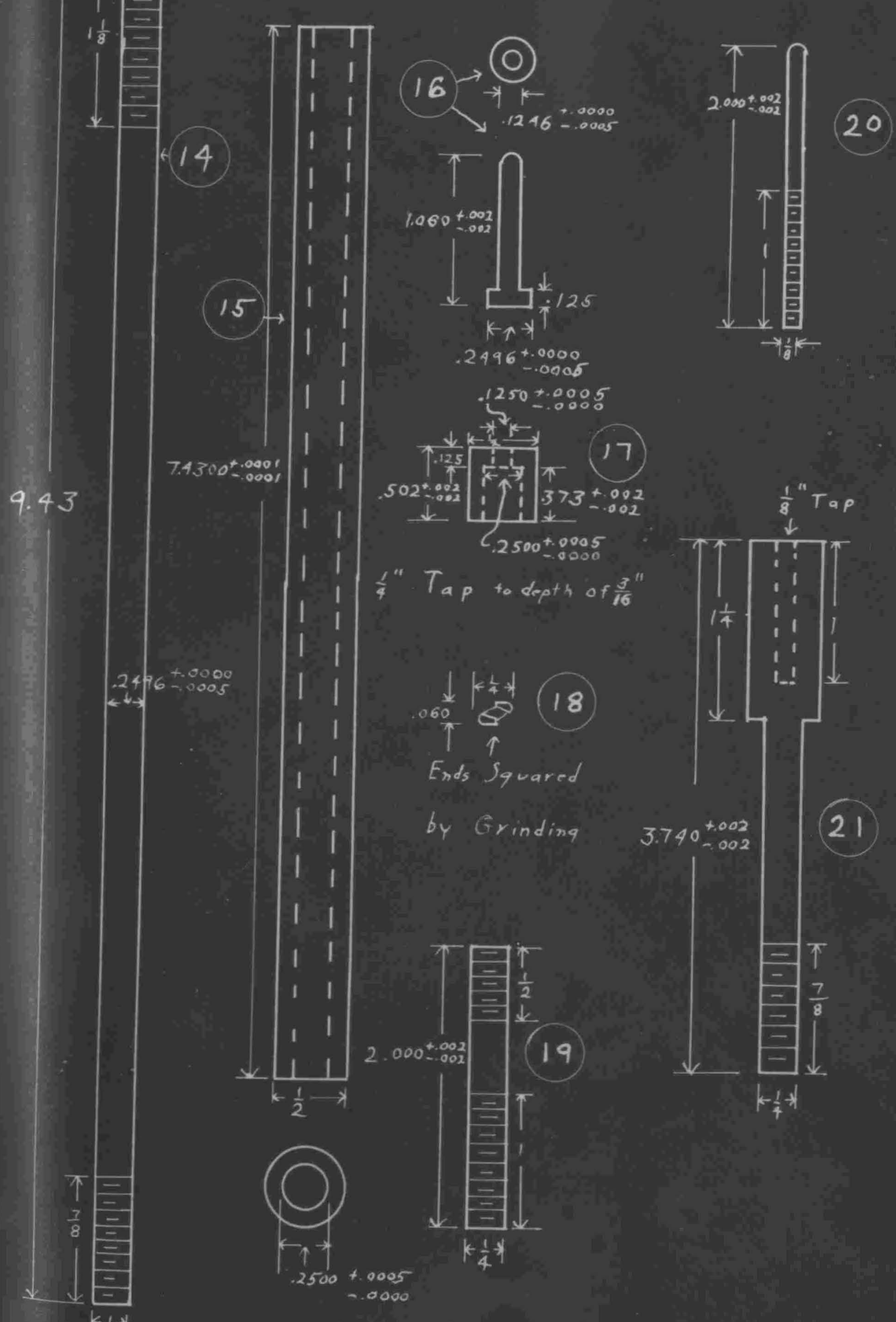


Illustration 3

Detail Drawing of Pieces No. 22-28

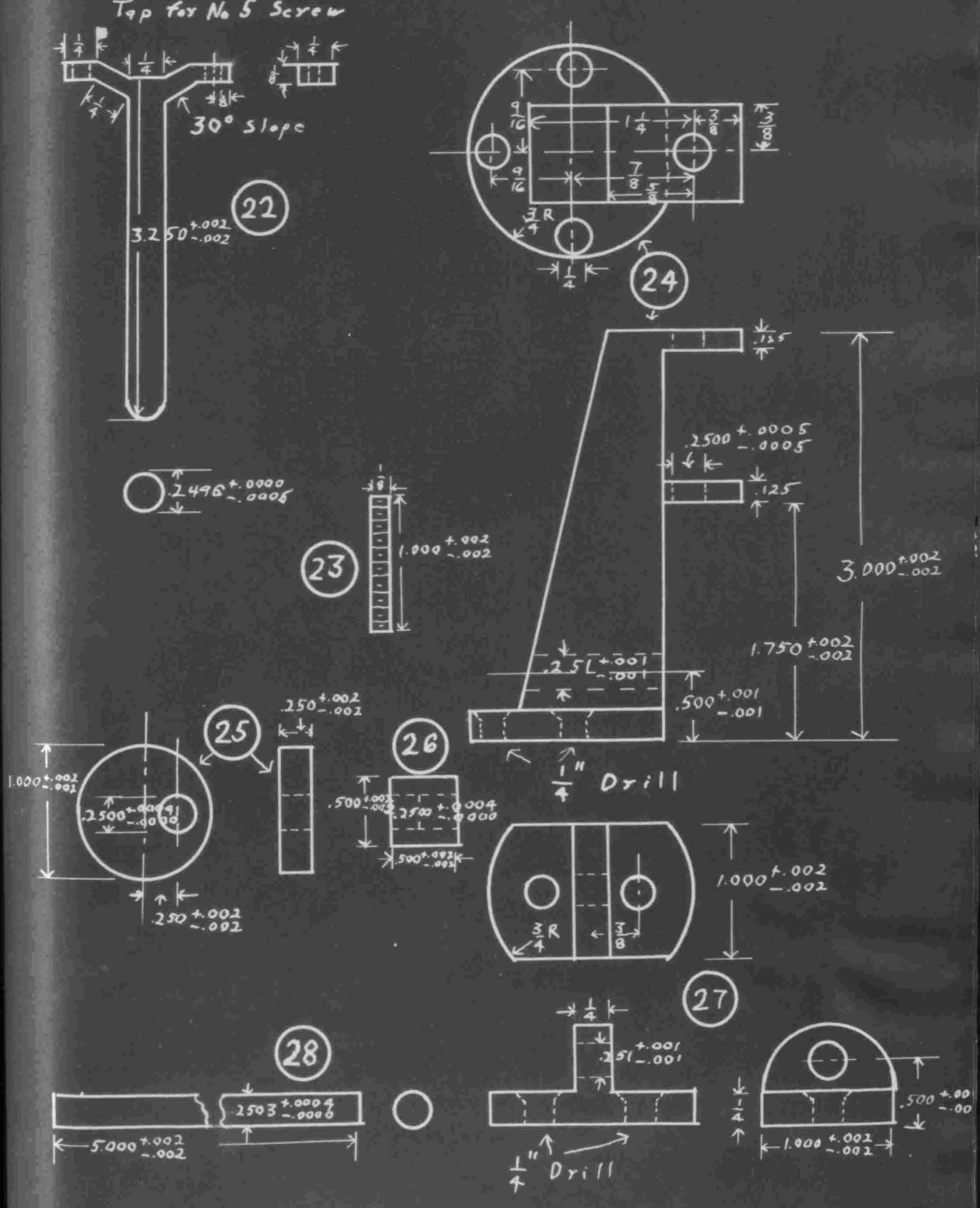


Illustration 4

Detail Drawing of Pieces No. 29-31

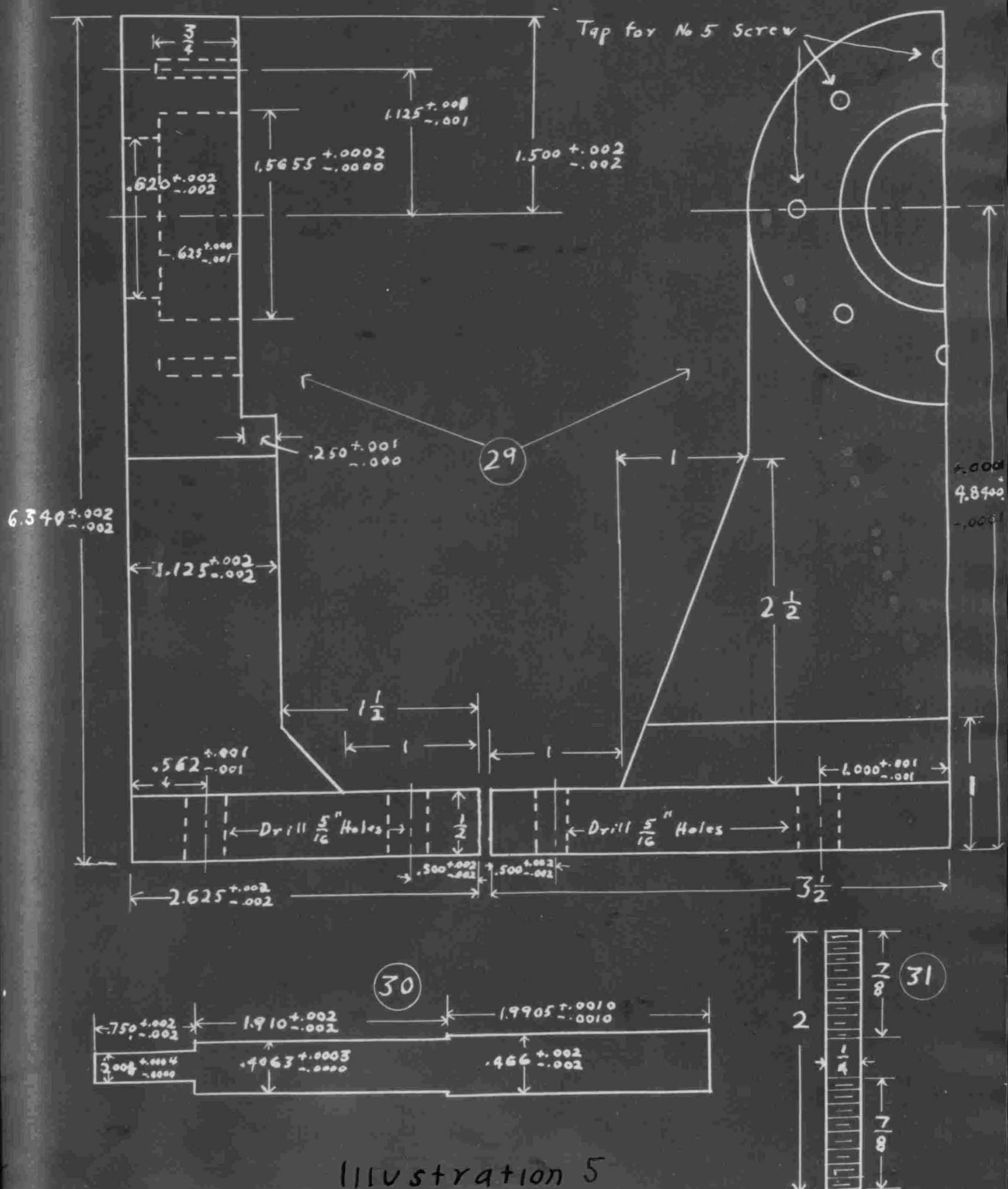
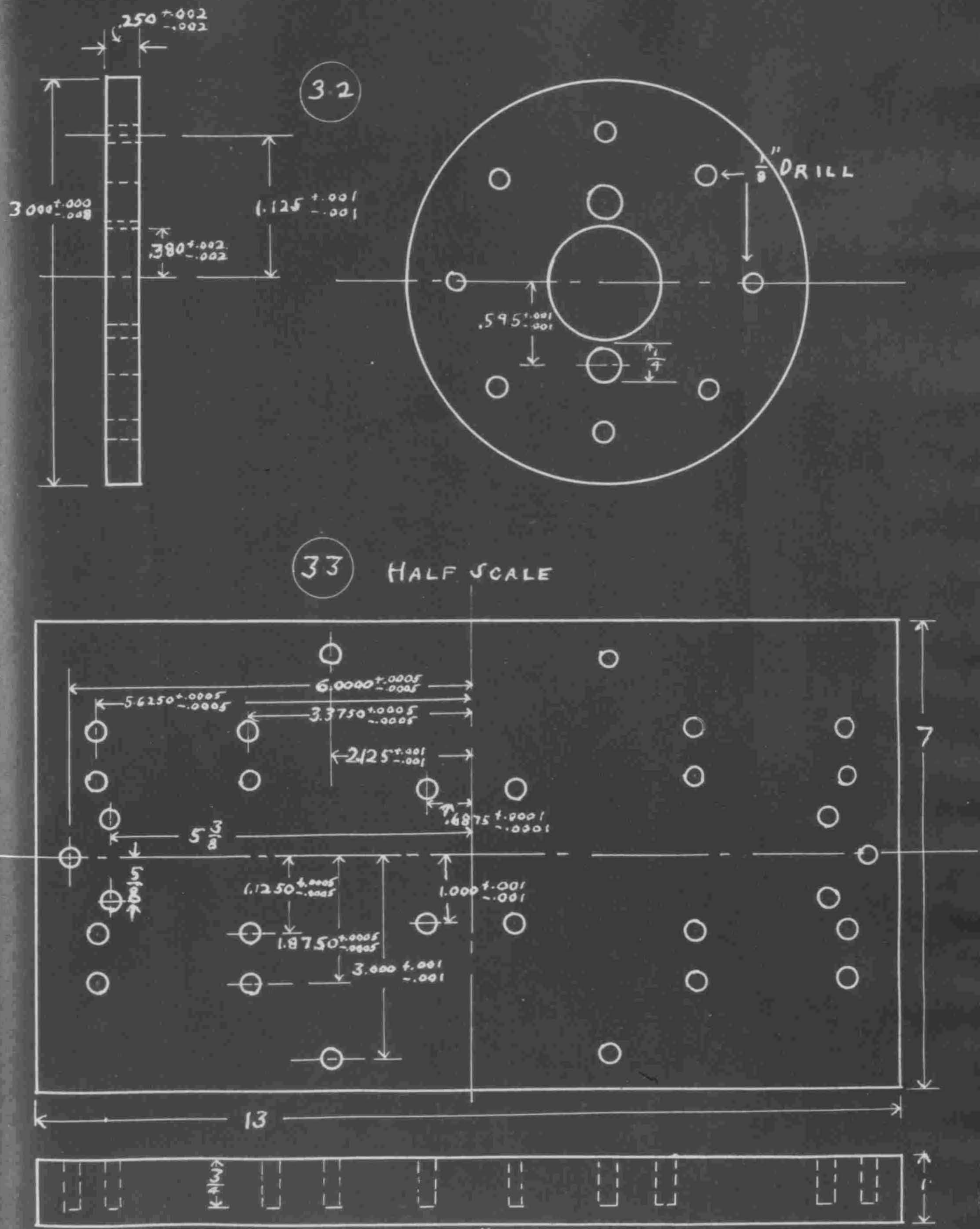


Illustration 5

Detail Drawing of Pieces No. 32-33



ALL HOLES 1/4" TAP

Illustration 6

Assembly Drawing
Left Side Elevation
(Full Scale)

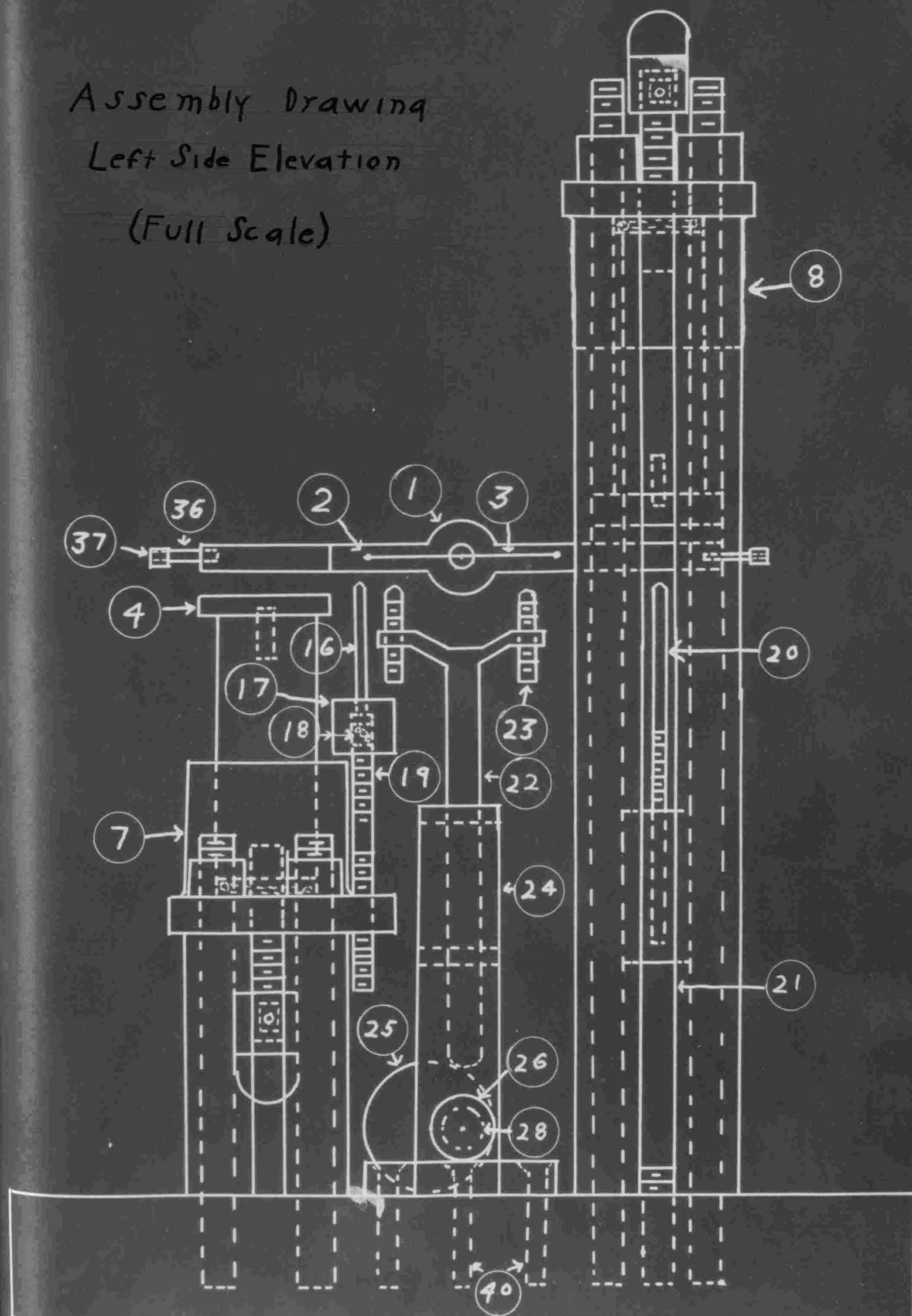


Illustration 7

Assembly Drawing
Front Elevation

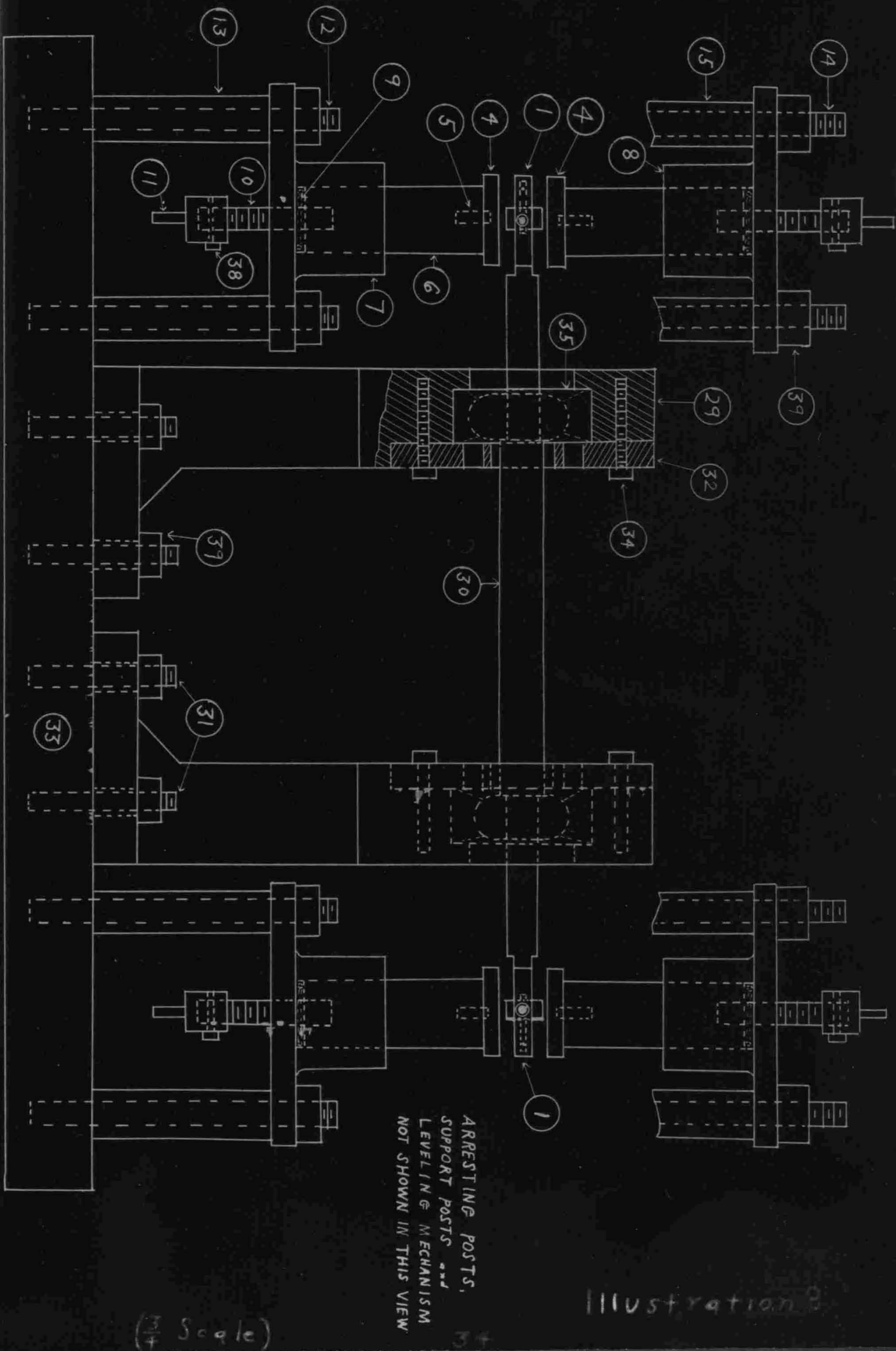


Illustration 9

(3/4 Scale)

BILL OF MATERIALS

PIECE NO.	NAME OF PIECE	NO. REQ'D	MATERIAL	REMARKS
1	CONDENSER DISC ARM	2	RY ALLOY TOOL STEEL	SEE NOTE 3
2	PEG	4	RY ALLOY TOOL STEEL	NO. 3 - 48 NC
3	WEIGHT WIRE	2	RY ALLOY TOOL STEEL	SEE NOTE 4
4	CONDENSER PLATE	4	RY ALLOY TOOL STEEL	
5	CONDENSER PLATE SCREW	4	RY ALLOY TOOL STEEL	NO. 5 - 40 NC
6	PLATE PEDESTAL	4	SEASONED MAPLE	
7	LOWER PEDESTAL GUIDE	2	STEEL-SAE-1030	
8	UPPER PEDESTAL GUIDE	2	STEEL-SAE-1030	
9	PEDESTAL SPRING	4	MUSIC WIRE	GAGE NO. 12 - 1 TURN
10	PEDESTAL SCREW	4	STEEL-SAE-1030	20 NC
11	THUMB SCREW	4	STEEL-SAE-1030	20 NC
12	LOWER PEDESTAL BOLT	8	STEEL-SAE-1030	20 NC
13	LOWER PEDESTAL BUSHING	8	STEEL-SAE-1030	
14	UPPER PEDESTAL BOLT	8	STEEL-SAE-1030	20 NC
15	UPPER PEDESTAL BUSHING	8	STEEL-SAE-1030	
16	ARRESTING POST	4	STEEL-SAE-1030	
17	ARRESTING POST GUIDE	4	STEEL-SAE-1030	
18	ARRESTING POST SPRING	4	MUSIC WIRE	GAGE NO. 22 - 1 TURN
19	ARRESTING POST SCREW	4	STEEL-SAE-1030	20 NC
20	SUPPORT POST	2	STEEL-SAE-1030	NO. 5 - 40 NC

Illustration 9

PIECE NO.	NAME OF PIECE	NO. REQ'D	MATERIAL	REMARKS
21	SUPPORT POST HOLDER	2	STEEL-SAE-1030	20 NC
22	LEVELING POST	2	STEEL-SAE-1030	NO. 5 - 40 NC
23	LEVELING POST SCREWS	4	STEEL-SAE-1030	NO. 5 - 40 NC
24	LEVELING POST GUIDE	2	STEEL-SAE-1030	
25	ECCENTRIC	2	STEEL-SAE-1030	
26	KNURLED KNOB	2	STEEL-SAE-1030	
27	HOUSING	2	STEEL-SAE-1030	
28	SHAFT FOR ECCENTRIC	2	STEEL-SAE-1030	
29	BEARING HOUSING	2	RY ALLOY TOOL STEEL	
30	SHAFT	1	RY ALLOY TOOL STEEL	
31	BEARING HOUSING SCREW	8	STEEL-SAE-1030	20 NC
32	BEARING RETAINING PLATE	2	STEEL-SAE-1030	
33	BEDPLATE	1	STEEL-SAE-1030	
34	BEARING PLATE SCREW	16	STEEL-SAE-1030	NO.5-40NC HEX. HD.
35	BEARING	2	SPECIAL STEEL	BARDEN-16-B-5
36	BALANCING SCREW	4	RY ALLOY TOOL STEEL	80 NC .5" LONG
37	BALANCING NUT	4	RY ALLOY TOOL STEEL	.125" LONG .125" DIA.
38	THUMB PIECE SCREW	4	STEEL-SAE-1030	NO. 2-56NC-FIL. HD.
39	NUTS	24	STEEL-SAE-1030	.250"-20NC-HEX.
40	ECCENTRIC HOUSING SCREW	10	STEEL-SAE-1030	NO.5-40NC OVAL HD.

Illustration 10

NOTES

1. ALL DIMENSIONS ARE IN INCHES.

2. ALL DRAWINGS ARE FULL SCALE EXCEPT WHERE INDICATED OTHERWISE.

3. CONDENSER DISC ARM IS TO BE CAREFULLY MACHINED TO DIMENSIONS SHOWN SO THAT IT WILL BALANCE ON A SHARP KNIFE EDGE. EXACT SPACING OF THE DISCS FROM THE CENTER IS NECESSARY. WHEN LAYING OUT THE CONDENSER DISC ARM, SCRATCH A FINE VERTICAL CENTER LINE ON THE ARM.

4. THREAD WIRE THROUGH PEGS AND CUT OFF EXCESS WIRE SO THAT EQUAL ENDS ARE LEFT FOR UPSETTING. FILE OFF ENOUGH OF ONE OF THE UPSET ENDS SO THAT THE ARM WILL STILL BE IN BALANCE.

LOW-LEVEL TORQUE GENERATING AND INDICATING MECHANISM

B. T. FRANA, LT-CDR, USN 7 APRIL 1949

U.S. NAVAL POSTGRADUATE SCHOOL

Illustration 11

CHAPTER IV

SELECTION OF THE ELECTRICAL EQUIPMENT

1. Batteries.

Two 300 volt dry cell batteries connected in series are used to supply the 600 volts desired. The connection between the batteries is used as a midtap.

2. Potentiometer.

A 50,000 ohm gang potentiometer (double coil) is connected to the midtap and the end battery terminals. The coils of the potentiometer must be closely matched. The use of the midtap serves to equalize the charges on the two series-connected condensers.

3. Voltmeter.

A high-precision high-resistance 600 volt Direct Current voltmeter is used to measure the potential difference applied to the condensers. The high resistance should be in the order of magnitude of 100,000 ohms to avoid shorting out the potentiometer. Two single-throw single-pole switches and a five foot length of No. 22 solid electrical hook-up wire complete the list of electrical equipment needed.

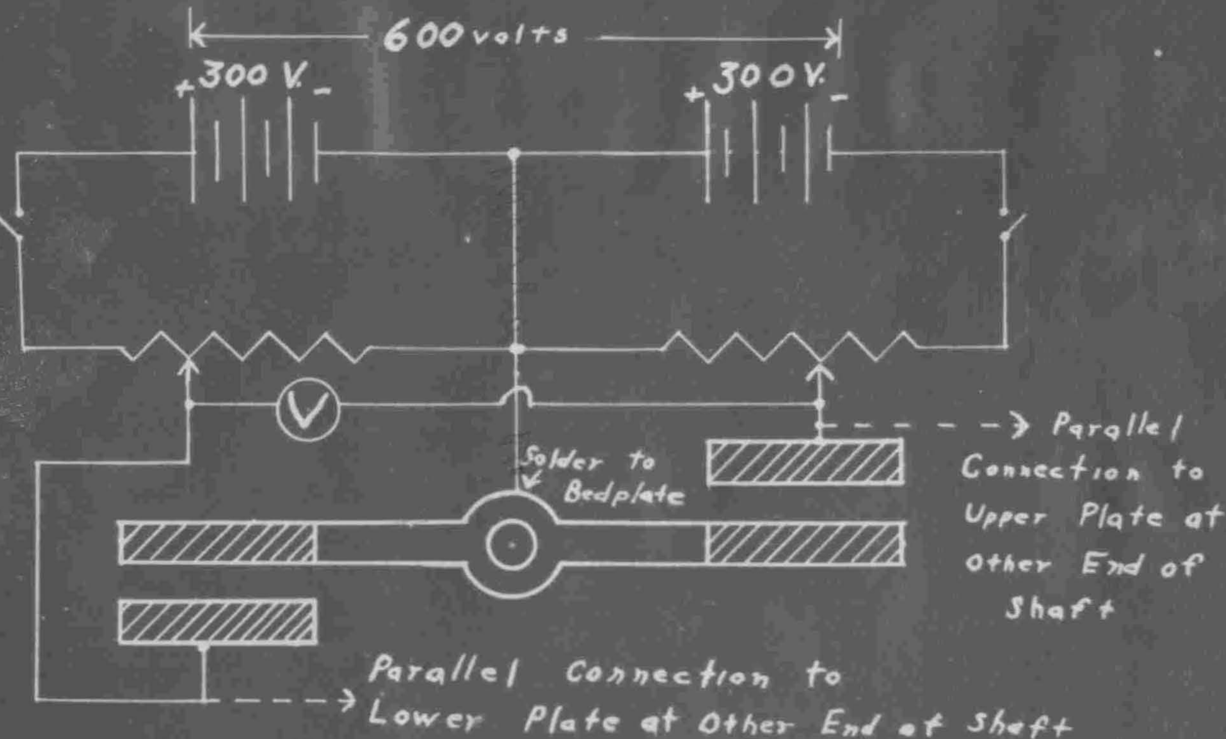
4. Circuit diagrams.

A circuit diagram and a schematic diagram of electrical equipment is shown in Illustration 12. The connection of the midtap to the bedplate serves as a ground. The connections to the condenser plates should be made by soldering.

5. Breadboard Layout.

The batteries, switches, potentiometer, and voltmeter may be mounted on a breadboard. By use of sufficient electrical lead wire the breadboard may be conveniently located. The breadboard layout is shown in Illustration 13.

CIRCUIT DIAGRAM



SCHEMATIC DIAGRAM of ELECTRICAL EQUIPMENT

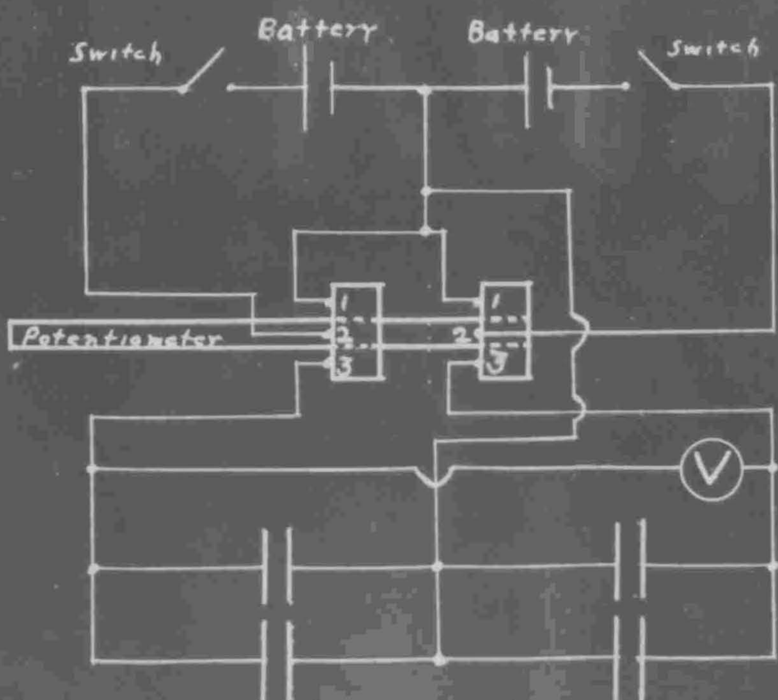


ILLUSTRATION 12

BREADBOARD LAYOUT

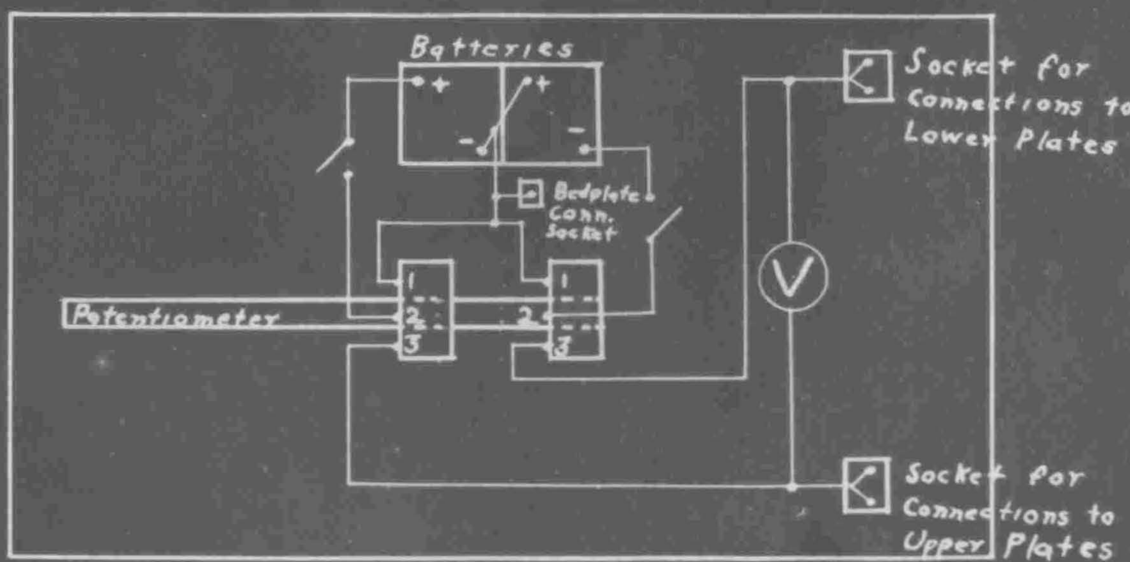


ILLUSTRATION 13

CHAPTER V

CARE OF MECHANISM

1. Protective Covering.

A protective covering, preferably of translucent plastic, is to be provided for each condenser disc arm and its associated condenser plates to protect this equipment from air currents and dust particles in the atmosphere during operation of the mechanism. A rectangular lucite casing without a bottom piece and of dimensions 6 inches long, 4 inches wide, and 10 inches high, with slots for the gyro rotor shaft and the shaft for the leveling attachment will cover the equipment at each end of the gyro unit. The gyro rotor shaft slots must have a covering which will fit closely around the shaft to exclude air that will be exhausted from the gyro casing.

To free the condenser plates and condenser discs from dust particles they should be wiped frequently during operation with soft leather soaked in benzol. This liquid has the property of preventing corrosion and should be used occasionally during non-operating periods. The benzol treatment should be used even though the equipment is protected by the covering because some dust particles might settle out of the air entrapped in the covering.

2. Prevention of Unnecessary Discharge of Batteries.

Discharge of the batteries can be prevented by the installation and use of a single-throw single-pole switch in each battery circuit as shown in Illustration 12.

The switches should be kept open except when the mechanism is in use.

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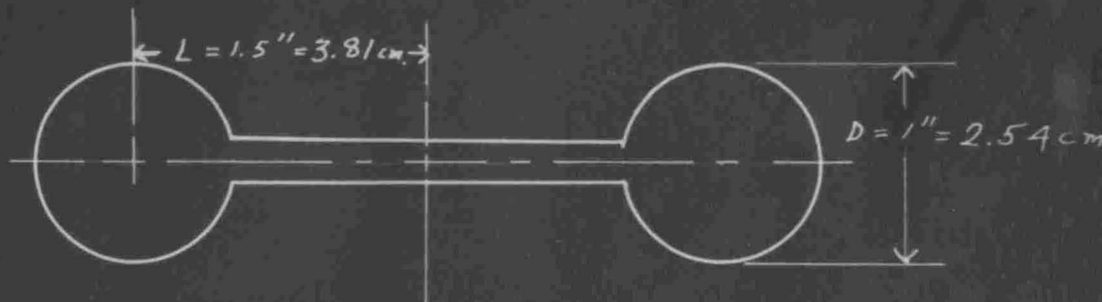
APPENDIX I

DETERMINATION OF CONDENSER DISC ARM DIMENSIONS



Assume

$D = 1$ in. $= 2.54$ cm, $L = 1.5$ in. $= 3.81$ cm., $t = 0.5$ cm $= 0.1968$ in.
and $s = 0.5$ cm. $= .1968$ in.

$$C_n = .0696\,\frac{D^2}{s} = .0696\,\frac{\overline{2.54}^2}{.5} = \frac{.0696 \times 6.49}{.5} = 0.907\ \mu\mu f$$

$$C_e = .0442\,D\left[\ln\frac{25.1\,D}{s} - 3 + Z\right]$$

$$= .0442 \times 2.54\left[\ln\frac{25.1 \times 2.54}{.5} - 3 + 1.39\right]$$

$$= .0442 \times 2.54\left[\ln 129.1 - 3 + 1.39\right]$$

$$= .1121\left[4.86 - 3 + 1.39\right] = .1121(3.25) = 0.362\ \mu\mu f$$

$$C_p = C_n + C_e = .907 + .362 = 1.269\ \mu\mu f$$

For $V = 100$ volts

$$f = \frac{1}{4}\,\frac{V^2}{s}\,C_p \times 10^{-5} = \frac{1}{4}\,\frac{10{,}000 \times 1.269}{0.5} \times 10^{-5} = 0.06345 \text{ dyne}$$

$T = 2L \times f$ for two series-condenser sets

$T = 2 \times 3.81 \times 0.06345 = 0.484$ dyne-cm.

For $V = 150$ volts $T = 1.09$ dyne-cm.
For $V = 600$ volts $T = 17.4$ dyne-cm.

Using the same D, L, and t, as before but letting s = 0.0625 in = 0.15875 cm.

$$C_n = .0696\frac{D^2}{s} = \frac{.0696 \times 2.54^2}{.15875} = 2.845 \text{ μμf}$$

$$C_e = \frac{D}{25.1}\left[\ln\frac{25.1(s+t)D}{s^2} + \frac{t}{s}\ln\frac{s+t}{t} - 3\right]$$

$$= \frac{2.54}{25.1}\left[\ln\frac{25.1 \times .6587 \times 2.54}{.15875^2} + \frac{.5}{.15875}\ln\frac{.65875}{.15875} - 3\right]$$

$$= .1011\left[\ln\frac{41.9}{.0253} + 3.50 \times 1.42 - 3\right]$$

$$= .1011\,(7.41 + 4.49 - 3) = (.1011)(8.90) = 0.900 \text{ μμf}$$

$$C_p = C_n + C_e = 3.745 \text{ μμf}$$

For V = 100 volts

$$F = \frac{1}{4}\frac{V^2}{s}C_p \times 10^{-5} = \frac{1}{4}\frac{10,000}{.15875} \times 3.745 \times 10^{-5} = 0.591 \text{ dyne}$$

$$T = 2L \times F = 2 \times 3.81 \times .591 = 4.51 \text{ dyne-cm.}$$

for V = 600 volts

$$T = 162.5 \text{ dyne-cm.}$$

APPENDIX II

CONSIDERATION OF SPURIOUS CAPACITANCE

By considering the path of the dielectric flux between the plate and the condenser disc arm it was calculated that an additive flux was present in the ratio of the width of the condenser disc arm to the circumference of the condenser disc. In like manner the flux caused by the balancing screw was additive and in the ratio of the diameter of the screw to the circumference of the condenser disc. The sum of the screw diameter and the condenser disc arm width of 0.0625 inches and 0.1968 inches is 0.2593 inches. The percentage that this value is of the condenser disc circumference is 8.24. The formulas for the edge effect capacitances are corrected to be

$$C_e = .0480\ D \left[\ln\left(\frac{25.1\ D}{s}\right) - 3 + z \right]$$

$$C_e = \frac{D}{23.15} \left[\ln\left(\frac{25.1 \quad (s + t)\ D}{s^2}\right) + \frac{t}{s} \ln \frac{s + t}{t} - 3 \right].$$

The effect of the arresting posts is subtractive since they are at the same potential as the condenser disc arms. Their dielectric effect compares with the normal effect of the condenser discs, that is, directly as the ratio of distances and inversely as the square of the diameters involved. The diameter of the arresting post is one-eighth inch and the distance of the top of the post from the condenser disc arm averages about three-fourths of the plate separation. This effect for each post is calculated as 2.08%. Since there are only two arresting posts and four condensers, consider the effect as 1.04% per condenser. Then the corrected formula for the normal capacitance is

$$C_n = .0689 \frac{D^2}{s},$$

No correction need be made for the leveling arms since the effect of one arm is neutralized by the effect of the other. Since the effect on the plates varies inversely as the square of the distance, the rest of the equipment is too far away from the condenser plates and condenser discs to produce any appreciable effect.

Torque-voltage curves as computed from these corrected capacitance formulas are in Appendix III. For actual use with the torque generating and indicating mechanism torque-voltage curves are plotted on a much larger scale.

APPENDIX III

PROCEDURE FOR USE OF TORQUE GENERATING AND INDICATING MECHANISM

Torque vs voltage curves for a separation of plates of 0.1968 inches and a separation of plates of 0.0625 inches are included in this appendix. These curves have been computed from formulas listed in appendix II.

The mechanism may be tested while mounted on the testing block. Or it may be tested while mounted on the gyro unit.

The steps in block-testing the mechanism are as follows:

1. Place condenser disc arm in the horizontal position by use of the leveling attachment.
2. Set accurately by means of gage blocks and feelers the separation between condenser discs and condenser plates.
3. Maintain constant the bearing loading conditions.
4. Retract the leveling attachment.
5. Apply voltage gradually until the condenser disc arm moves, that is, until breakaway torque is generated. Repeat application of voltage several times (about 20). Ascertain the mean value of these voltages.
6. Enter the torque-voltage curve for the separation in use with this mean voltage value and read the corresponding torque.

7. Relevel the condenser disc arms and move the support posts into contact with the condenser discs.

8. Apply the voltage gradually. By repeated applications determine the exact voltage necessary. From the curve read the torque for breakaway with the support posts in contact position. (The torque caused by the contact adhesion of the tips of the support posts may be checked by use of weights placed on the weight wire at a distance from the center of gravity of the condenser disc arm.)

9. With the support posts in contact position, add a known weight on the weight wire. Scale beam riders whose weight had been accurately checked are to be used as weights.

10. Measure the distance of the weight from the center of the condenser disc arm with a comparator. The product of the measured distance and the weight will produce an increment of torque in excess of the breakaway torque. The term "total breakaway torque" will be used for the sum of the breakaway torque (with the support posts in contact) and the increment torque.

11. By repeated tests determine the exact voltage necessary for each total breakaway torque corresponding to each increment of torque obtained by additional weights and greater distances.

The measured voltages with their corresponding total breakaway torques should check within experimental error with the computed values on the curves included in this appendix.

The fluid bearings chosen for the test block arrangement have very low breakaway torque characteristics. Below this breakaway torque point the computed torque-voltage curve should be used unless the experimental values differ consistently from the computed values. In which case plot the experimental values and extrapolate the curve below the lowest breakaway torque point. The breakaway torque of the bearings can be checked by use of weights without the support posts in contact position.

The mechanism may be tested with the bedplate at any angle with the horizontal. It must be remembered that the increment torque applied varies as the sine of that angle.

The steps in generating and indicating breakaway torque in the gyro unit are as follows:

1. Level the condenser disc arm.
2. Set accurately by means of gage blocks and feelers the separation between condenser discs and condenser plates.
3. Maintain constant the gyro air-support conditions.
4. Retract the leveling attachment.
5. Determine the mean voltage necessary for breakaway torque by several repeated trials.

6. Enter the breakaway torque-voltage curve for the separation in use with the mean voltage and pick off the corresponding breakaway torque.

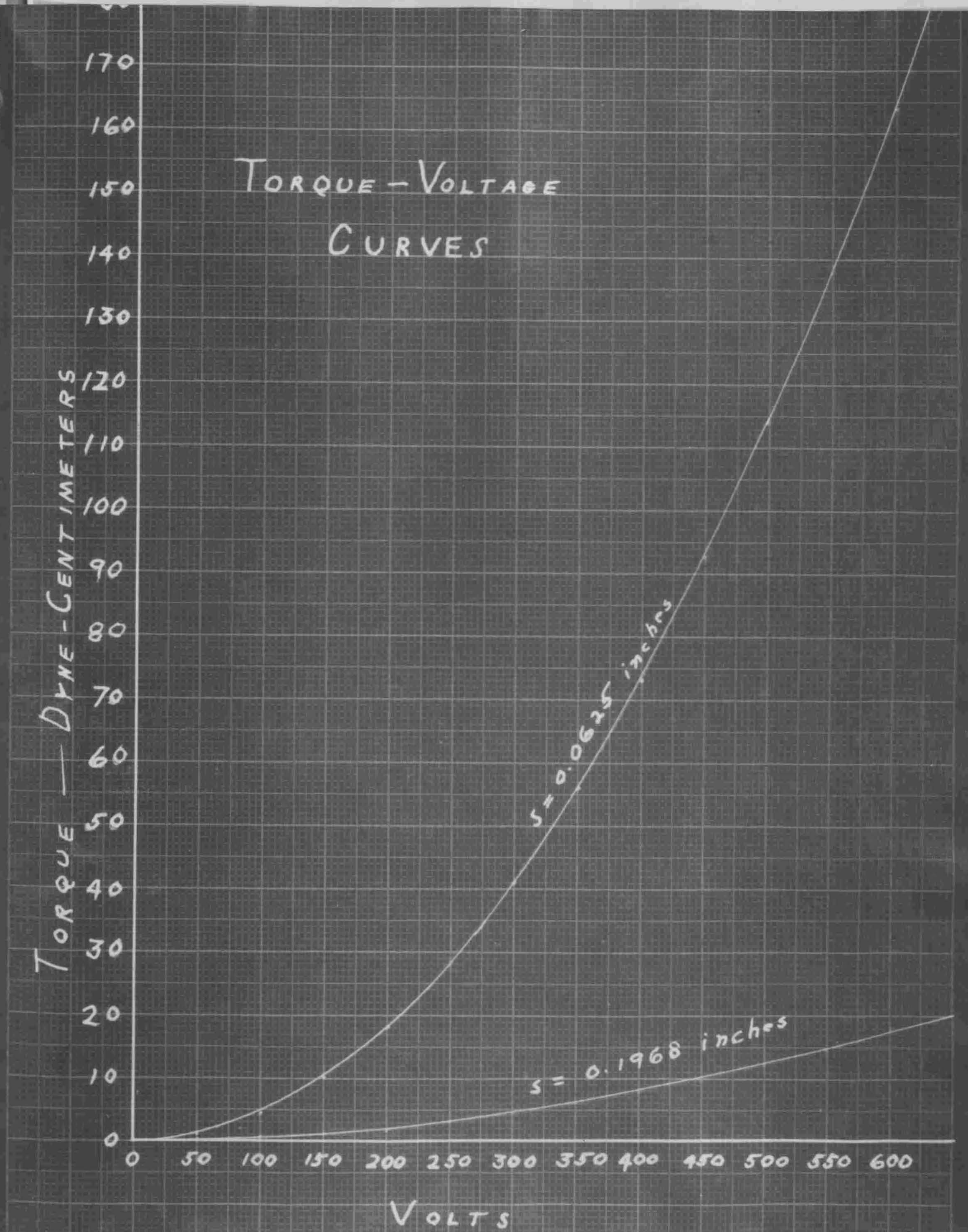


Illustration 14

APPENDIX IV

EXPECTED ACCURACY

The accuracy of the mechanism will depend on the exactness in construction and the care in operation. Features of construction that require especial care are the exact machining of the condenser disc arm and the condenser plates. Their faces must be parallel and flat. The condenser disc arm must be in balance. Care must be exercised in assembling the plates and disc arms so that the plates are co-axial.

Batteries of equal potential must be used. Potentiometers with balanced coils must be selected. The plastic casing should be used when the mechanism is being operated. The separation between plates should be accurately set with gage blocks and feelers.

The National Bureau of Standards has made several interesting tests on an Absolute Electrometer. Brooks (7). This electrometer uses the principle of force produced by voltage on a parallel plate condenser. Efforts were made to produce partial breakdown of the dielectric--a phenomenon which is known as "electric wind". The changes caused by the electric wind were less than the precision at the time these experiments were made. To see whether dust particles produced appreciable error, cotton fibers were laid on one of the plates. No consistent change in the performance of the electrometer appeared.

If the present design of the gyro unit is finally selected for manufacture, the gyro will have a possible axial movement of 0.001 inches. When the condenser disc arms are mounted on the shaft, they should be centered at the midpoint of this 0.001 inches so that it will be possible for the condenser discs to be out of co-axialism with the condenser plates by only + 0.0005 or - 0.0005 inches. It can be only a matter of conjecture just what form the dielectric flux will assume when the discs and plates are out of co-axialism. This is probably the reason no published analysis is available on this subject. An approximate analysis is that the capacitance is decreased in the ratio of the square of the amount of the overlap portion of the plate out of co-axialism to the square of the diameter of the other plate. On this basis the decrease in capacitance is 0.1% when maximum misalignment of 0.0005 inches exists. This is well within experimental error and may be considered negligible.

Measurements of torque should be made under standard temperature conditions. Inaccuracies due to temperature differences that are within 10 degrees Farenheit of the standard temperature may be considered negligible. Brooks (7).

If the construction and operation of the mechanism are carefully accomplished, it is expected that the computed and measured values will be the actual values within experimental error. Experiments by the National Bureau of Standards have shown that for the size of capacitors used in this mechanism an accuracy of about 0.1 percent can be obtained. Moon (35)